Effects of two-phase flow friction factor correlations on the optimal pressure drop-Martinelli Parameter pair in a mini-channel

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Abstract. Substantial research has been completed with more on-going on the flow pattern and heat transfer associated with two-phase flows. Discrepancies reported may have been as much as agreements, due to the different models, approaches, flow regimes, correlations, and new working fluids being utilized. This paper reports the outcome of a study to look at the effects of applying two different friction factor correlations on the simultaneous minimization of the pressure drop and Martinelli parameter under optimized flow rate and vapor quality, using genetic algorithm. The homogeneous model is assumed with ammonia as the working fluid, the coolant being environmentally friendly and having recently discovered as a potential replacement for the current refrigerants in micro and mini-channels. Results show that significant differences in the frictional pressure drop and Martinelli parameter arise due to the different correlations used, and this is only the outcome from two different correlations currently being considered by researchers in pressure drop analysis for two-phase flows in mini-channels. Thus, absolute agreement is indeed not possible between theoretical, experimental, and numerical work in view of the many different available correlations being utilized today with differences between 10 to 100 percent that has already been established.

Introduction

Increasing demand for decreasing sized heat exchangers has posed serious challenges to researchers involved in the already unpredictable flow and thermal field of two-phase flows. There are two general methods that have been used to model the two-phase flow; the separated model and the homogeneous model. The simpler homogeneous model assumes that both the liquid and vapor components in the two-phase flow are having the same velocity whilst the separated model treats each phase as a separate entity [1]. The many correlations for pressure drop and Nusselt numbers proposed to represent the phenomena are now faced with suitability and reliability in applications with smaller channels. The numerous empirical relationships between the relevant parameters that contribute towards the pressure drop and heat transfer coefficients have been developed since many decades ago, over countless experimental data obtained under controlled conditions [2].

The friction factor that affects the pressure drop in a turbulent two-phase flow within pipes probably started with the Nikuradse equation [3] which covers the smooth portion of the Moody diagram [4]. However, the Nikuradse equation and subsequent ones, which pioneered friction factor calculations are implicitly defined and thus require an iterative procedure. Several friction factor correlations were formulated later and this study looks at the outcome of applying two different friction factor correlations for turbulent flow that are currently being used on the calculations of the pressure drop and Martinelli parameter for a mini-channel. They are the explicit forms proposed by Fang et al. [5] and that used by Kim and Mudawar [6]. The study has been undertaken to look at the effects of using these different correlations when an optimization tool is implemented, minimizing two objectives under optimized conditions of the chosen relevant parameters. The objectives are the pressure drop and the Lockhart-Martinelli parameter (here onwards referred to the Martinelli parameter for short), both selected because they affect the vapor quality and complete vaporization maybe controlled in the thermal management of the system.The two parameters have opposite effect on each other and thus is suitable for use with the genetic algorithm optimization tool, which to the authors knowledge has never been applied in this case before. This study assumes the homogeneous model and the two parameters to be optimized are the flow rate and vapor quality.

Theoretical Formulation

Although there are two widely accepted models to generally represent two-phase flows in mini-channels, the separated and the homogeneous model, the latter is chosen due to its simplicity in this initial investigation using an evolutionary algorithm to analyse the pressure drop of the flow. Liquid ammonia is the working fluid since it has recently been found to be a potential coolant for the replacement of current non-environmentally friendly refrigerants. The thermophysical properties have been obtained from Pamitran et al. [7].

The pressure drop is made up of the friction, acceleration, and static head components. However, the frcitional pressure drop is considered to be the most significant and often only retained. Choi et al. [8] stated that the homogeneous model could well predict the frictional pressure drop. It is given by [2],

$$\left(\frac{\Delta P}{\Delta L}\right)_{tp} = \frac{G_{tp}^2}{2\rho_{tp} D} f_{tp} \qquad (1)$$

with the first of two two-phase friction factors for turbulent flowtaken to be [5],

$$f_{tp} = 0.25\left[log\left(\frac{150.39}{Re^{0.98865}} - \frac{152.06}{Re}\right)\right]^{-2} \qquad (2)$$

and the second [6],

$$f_{tp} = 0.046 Re_{tp}^{-0.2}. \qquad (3)$$

The terms G_{tp}, ρ_{tp}, Re, and D stand for the two-phase flow rate, density and Reynold number, and channel diameter respectively. The two-phase density is determined from McAdams et al. [9],

$$\frac{1}{\rho_{tp}} = \frac{x}{\rho_g} + \frac{1-x}{\rho_l} \qquad (4)$$

Meanwhile, the Martinelli parameter is defined by,

$$X = \sqrt{\frac{(\Delta p/\Delta L)_l}{(\Delta p/\Delta L)_g}}, \qquad (5)$$

where when simplified becomes,

$$X = \left(\frac{f_f}{f_g}\right)^{1/2}\left(\frac{1-x}{x}\right)\left(\frac{\rho_f}{\rho_g}\right)^{1/2}. \qquad (6)$$

The subscripts f and g refer to the liquid and vapor components whose properties in this study have been obtained from Pamitran et al. [7]. Eq. 5 formed the foundation of the two-phase friction multipliers, their determination being the subject of numerous studies in identifying the most appropriate constants that made up the equation [2]. Eq. 6 is being coupled with the pressure drop in the current homogeneous model because it represents the two-phase quality in terms of its properties.

Looking at Eq. 1 and Eq. 5, it can be seen that as the vapor quality increases, the Martinelli parameter decreases while the pressure drop increases. In two-phase flow in heat exchangers, it is highly desirable to have the pressure drop as low as possible while the vapor quality increases as the coolant passes through the tube. Thus, the current problem is suitable for use with genetic algorithm whereby the two objectives have opposite effects on each other though the minimization of both is the goal. In this study, the optimized flow rate as well as the vapor quality is searched for during the minimization of the two objective functions. Matlab multi-objective optimization toolbox is utilized to achieve the minimization of equations (1) and (4) subjected to 50 kg/m^{2}sec $<G<$600 kg/m^{2}sec and 0 $<$ x$<$ 0.8, the upper limit for the quality being chosen based on experimental experience. Table 1 lists the properties of ammonia used in this study and other parameters associated with the properties obtained.

Table 1: Properties of ammonia used in the study [7].

Diameter of tube [mm]	1.5	Vapor phase density [kg/m^3]	4.1
Mass flow rate [g/min]	22-53	Liquid phase viscosity [μPa.s]	161
Working pressure [Mpa(abs)]	0.515	Vapor phase viscosity [μPa.s]	9.2
Flow rate [kg/m^{2}s]	100-500	Reynolds number	1875-4575
Heat flux [kW/m^2]	40-70	Saturation temperature [°C]	5
Liquid phase density [kg/m^3]	631.7		

Results and Discussions

The optimization process was completed five times for each friction factor used and the average output is presented here. Figure 1 shows the minimized pressure drop per unit length against the minimized Martinelli parameter under optimized vapor quality and flow rate. Significant difference is observed particularly as the pressure drop increases, which physically normally occurs downstream of the pipe. The simpler frictional pressure drop equation of Kim and Mudawar [6] has a much lower pressure drop at the same Martinelli parameter, which is translated into for the same vapor quality. Since this is a stochastic approach which tries to determine the most probable optimized flow rate and vapor quality to minimize the pressure drop and Martinelli parameter, use of a simpler frictional pressure drop correlation seems to affect a lower pressure drop along the minichannel. The optimal Pareto front obtained from using Eq. 2 and Eq. 3 has the same number of solutions.Xu et al. [2] stated that Eq. 2 is the most accurate explicit single-phase friction factor for turbulent flow in a smooth pipe appearing in two-phase friction factor pressure drop correlations. Eq. 3 is used for comparison in this study because it was proposed by Kim and Mudawar [6] in a recent paper.

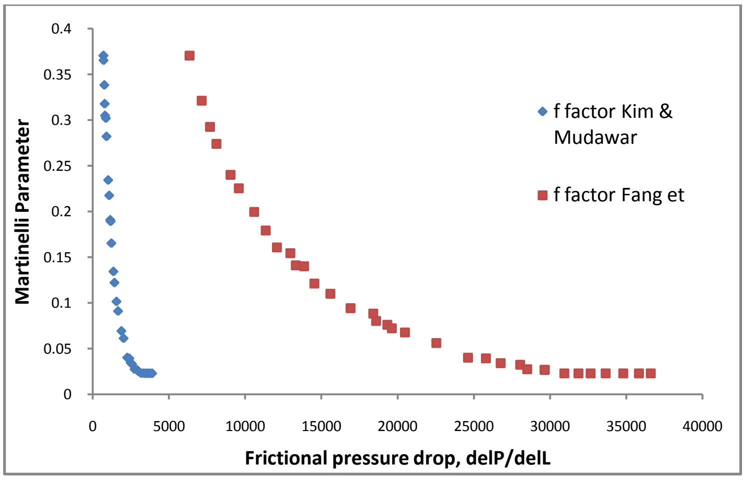

Figure 1: Martinelli parameter against the frictional pressure drop.

The graph for the pressure drop against the vapor quality as shown in Fig. 2 is similar to those that have been reported experimentally [2]. Since the current preliminary study only looks at the vapor quality up to 0.8, nothing could be compared there after. Past numerical studies have shown a continuous increase while experimental data showed a downward turn after it peaks at a quality between 0.6 and 0.8, the location of which depends on the onset of dry-out.Huge differences are seen in Fig. 3 for the graph of frictional pressure drop against the optimized flow rate. Again, at each flow rate the use of the simpler Eq. 3 gives a much lower frictional pressure drop compared to the outcome of using Eq. 2. The latter also gives a large increase in pressure drop over a small range of optimized flow rate. Both correlations indicate that the optimized flow rate is under 70 kg/m^2.sec if the frictional pressure drop and Martinelli parameter are to be minimized.

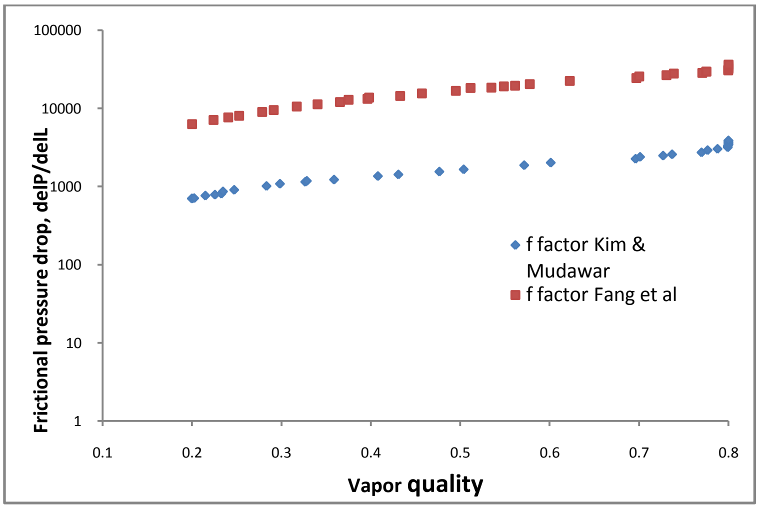

Figure 2: Frictional pressure drop against optimized vapor quality.

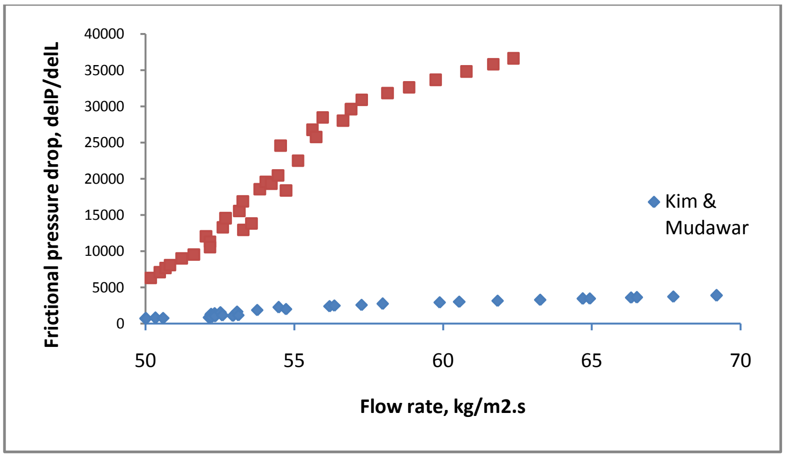

Figure 3: Frictional prssure drop against optimized flow rate.

The present outcome of optimization with genetic algorithm has shown what has been expected qualitatively, that there are differences in the calculated pressure drop when different frictional pressure drop correlations are used and new ones are being developed just to address this issue. Discrepancies between predicted and experimental data have been reported up to 100% [5]. Even Eq. 4 is just one of many being used to determine the two-phase density. Although this optimization scheme is one-dimensional with many of the physical properties that could have affected the pressure drop, Martinelli parameter and quality, have been ignored, the expected trend and pattern that was achieved quickly shows the capability of the tool to assist in the identification of the pressure drop pattern particularly with exploratory type of research, to supplement the theroretical and experimental research of the complex two-phase flow. The advantage of using the present optimization scheme of multi-objective genetic algorithm is that it is a fast tool which could identify optimized conditions for operations to minimize the pressure drop. This is just the beginning of a research project to look at the feasibility of the genetic algorithm scheme as a tool to predict the pressure drop and vapor quality of two-phase flows in mini and microchannels of heat exchangers. The outcome indicate a promising application and the next step is to investigate the pattern using other frictional pressure drop and Martinelli parameter correlations to determine how close each is to the experimental data collected.

Conclusion

The effects of using two different friction factor correlations in the calculations of the frictional pressure drop have been predicted using multi-objective genetic algorithm. The relationship between the pressure drop and Martinelli parameter is as expected with a significant difference being the outcome of using the two different correlations. Similar pattern and trends with past numerical studies are observed. The application of MOGA as an optimization tool has shown the potential of identifying optimized conditions. The results so far show what has been established experimentally, absolute agreement is near impossible in view of the differences in coolants tested under different controlled conditions. It is hoped that the fast optimization tool can assist researchers who are directly involved in experimental work in two-phase flow to complete their data collection under optimized conditions and thus minimization differences between correlations. The higher energy efficiency associated with two-phase flows compared to that of a single phase emphasized the need for smaller error and fast tools.

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References

[1] R. Revellin, S. Lips, S. Khandekar, and J. Bonjour, Local Entropy Generation for saturated two-phase flow, Energy. 34 (2009) 1113-1121.

[2] Y. Xu, X. Fang, X Su, Z Zhou, and W Chen, Evaluation of frictional pressure drop correlations for two-phase flow in pipes, Nuclear Engineering and Design. 253 (2012) 86-97.

[3] J. Nikuradse, Stromungsgesetze in rauhenRohren, Ver. Dtsch. Ing. Forsch. 361 (1933), 1-22.

[4] L. F. Moody, Friction factors for pipe flows, Trans. ASME. (1944) 671-684.

[5] X. D. Fang, H.G. Zhang, Y. Xu, and X. H. Su, Evaluation of using two-phase frictional pressure drop correlations for normal gravity to microgravity and reduced gravity, Adv. Space Research. 49 (2011) 351-364.

[6] S.M. Kim and I Mudawar, Universal approach to predicting two-phase frictional pressure drop for mini/micro-channel saturated flow boiling, Int. J. Heat and Mass Transfer. 58 (2013) 718-734.

[7] A.S. Pamitran, K.I. Choi, J.T.Oh, and P. Hrnjak, Characteristics of two-phase flow pattern transitions andpressure drop of five refrigerants in horizontal circular small tubes, International Journal of Refrigeration. 33 (2010) 578-588.

[8] K.I. Choi, A.S. Pamitran, C.Y.Oh, and J.T. Oh, Two-phase pressure drop of R-410A in horizontal smooth minichannels, Int. J. Refrigeration. 31 (2008) 119-129.

[9] W.H. McAdams, W.K. Wood, and R.L. Bryan, Vaporization inside horizontal tubes-II-benzene-oil mixtures, Trans. ASME. 66 (1942) 671-684.